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13. ABSTRACT (*Maximum 200 words*)

Research is reported on the dynamic shearing response of three metals: OFHC copper, tantalum,and 4340 VAR steel. For OFHC copper the important new result is that the flow stress has been measured at strain rates up to 1,000,000/sec at temperatures up to 700 C. At the elevated temperatures the dynamic plastic response is remarkably stable and the flow stress is considerably higher than predicted by commonly used constitutive models. For tantalum foils the behavior at strain rates greater than 100,000/sec appears to be described quite well by a smooth extension of the previously measured response at lower strain rates. Again, the plastic flow at high strain rates appears to be remarkably stable. For 4340 VAR steel, a new pressure-shear plate impact experiment has been developed to impose Mode II or Mode III loading. Pilot experiments have shown a shear-like, relatively flat failure surface. Further interpretation of the latter experiments must be deferred until the effects of a reflected tensile wave are eliminated.

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on Research Award:

Plastic Flow and Shear Banding in Refractory Metals and Martensitic Steels at Very High Shearing Rates

Award No.: DAAH04-94-G-0233

from

Rodney J. Clifton, Principal Investigator
Division of Engineering
Brown University
Providence, RI 02912

June 26, 2001

ABSTRACT

Research is reported on the dynamic shearing response of three metals: OFHC copper, tantalum, and 4340 VAR steel. For OFHC copper the important new result is that the flow stress has been measured at strain rates up to $10^6 s^{-1}$ at temperatures up to $700°C$. At the elevated temperatures the dynamic plastic response is remarkably stable and the flow stress is considerably higher than predicted by commonly used constitutive models. For tantalum foils the behavior at strain rates greater than $10^5 s^{-1}$ appears to be described quite well by a smooth extension of the previously measured response at lower strain rates. Again, the plastic flow at high strain rates appears to be remarkably stable. For 4340 VAR steel, a new pressure-shear plate impact experiment has been developed to impose Mode II or Mode III. Pilot experiments have shown a shear-like, relatively flat failure surface. Further interpretation of the latter experiments must be deferred until the effects of a reflected tensile wave are eliminated.

1. Dynamic Shearing Resistance of Materials at Elevated Temperatures

The pressure-shear plate impact experiment has been modified to test materials at high temperatures (up to 700 $^{\circ}C$). Together with the high strain rates characteristic of this experiment ($10^6\ s^{-1}$), the high temperature capability allows the shearing resistance of materials to be measured at states unattainable with other testing equipment. The current testing capability of this technique as a function of temperature and strain rate is highlighted by the dark shading in Figure 1. A thin plate of the specimen material is

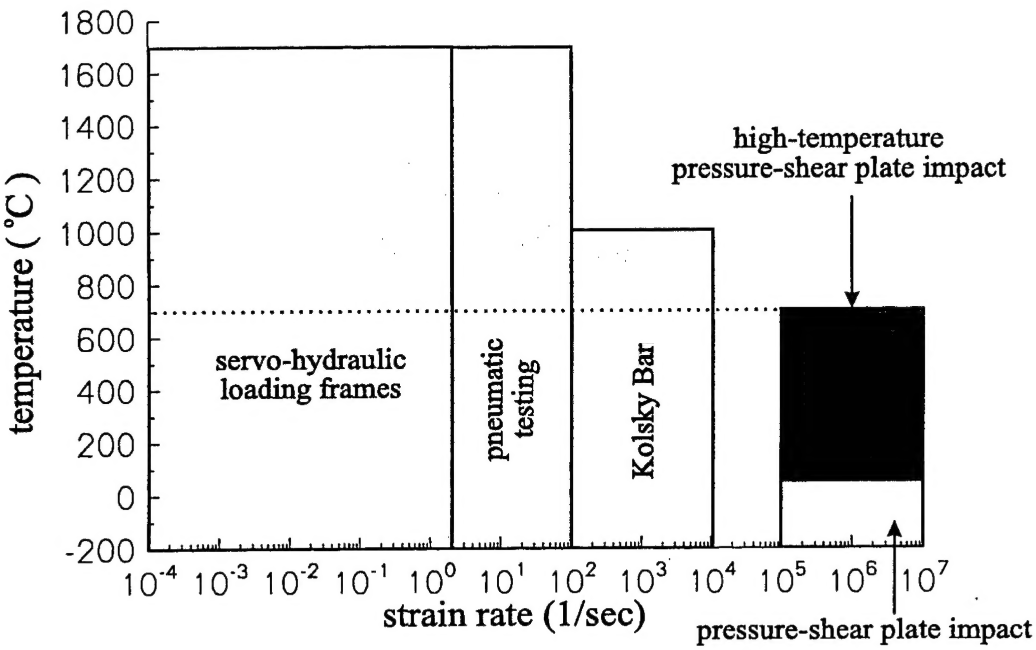

Figure 1: Survey of Mechanical Testing Methods

sandwiched between two pure tungsten carbide plates which, through pressure-shear symmetric impact experiments, have been shown to have sufficient high temperature strength to remain elastic under the temperature and loading conditions of the experiment. This assembly is heated by an induction heating coil that surrounds it as shown in Figure 2. To overcome possible misalignment of the impact face of the target due to thermal expansion of the target supports, the alignment of the target assembly is maintained by using an optical lever approach in which a laser beam reflected from the rear surface of the target is displayed on a distant screen. Remote

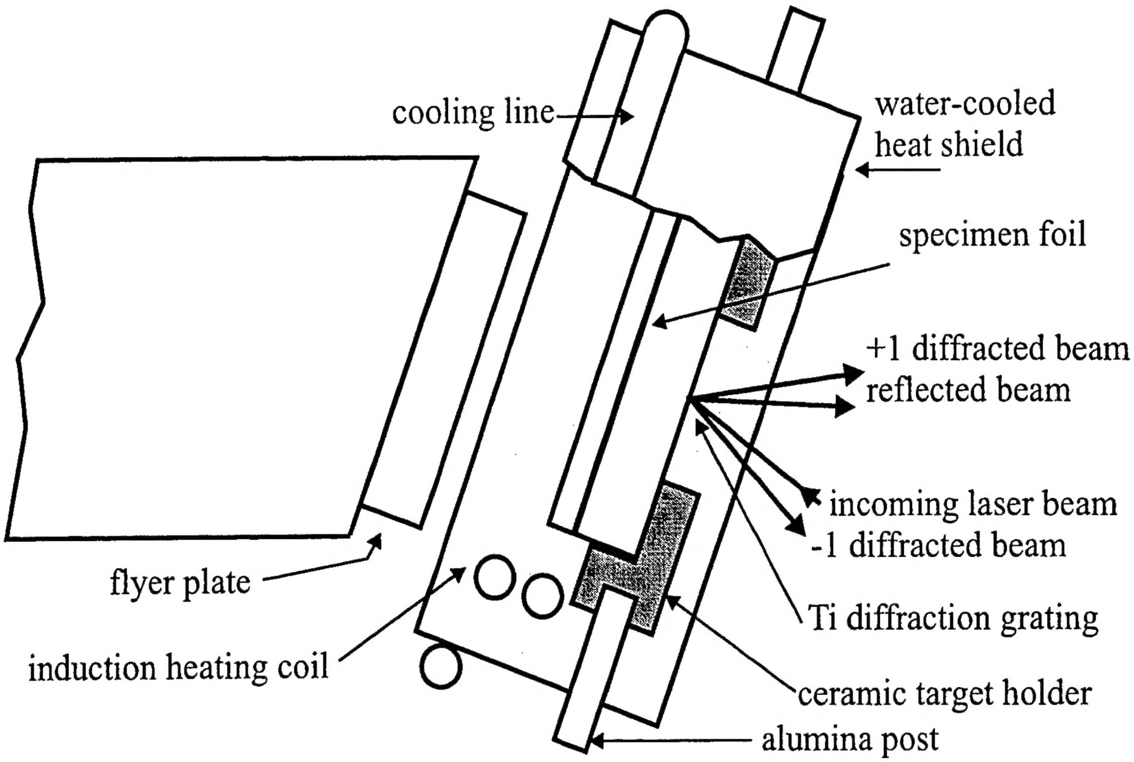

Figure 2: Schematic of Configuration for High-Temperature, Pressure-Shear Experiment

controls are used to realign the target assembly to maintain its original alignment with the impact face of the flyer plate. Photoresist gratings, which normally provide the diffracted beams used in recording the transverse velocity of the target assembly, are replaced by metallic phase gratings produced by SEM lithography — resulting in the deposition of titanium strips on the rear surface of the target assembly.

As a first application of this capability, the flow stress of OFHC copper has been investigated over temperatures from $300°C$ to $700°C$ and strain rates from 10^5 to $10^6 s^{-1}$. The dynamic stress-strain curves obtained from these experiments are shown in Figure 3.

These curves should be viewed as representing material response under nominally homogeneous states of stress and strain after shear strains of 0.04 – 0.1, and 0.3 for tests at nominal shear rates of $2.5 \times 10^5 s^{-1}$ and $1.2 \times 10^6 s^{-1}$, respectively. From these curves it is evident that the flow stress increases with increasing strain rate and decreases with increasing temperature over the range of strain rates and temperatures considered. At the higher strain rate, softening occurs after strains of

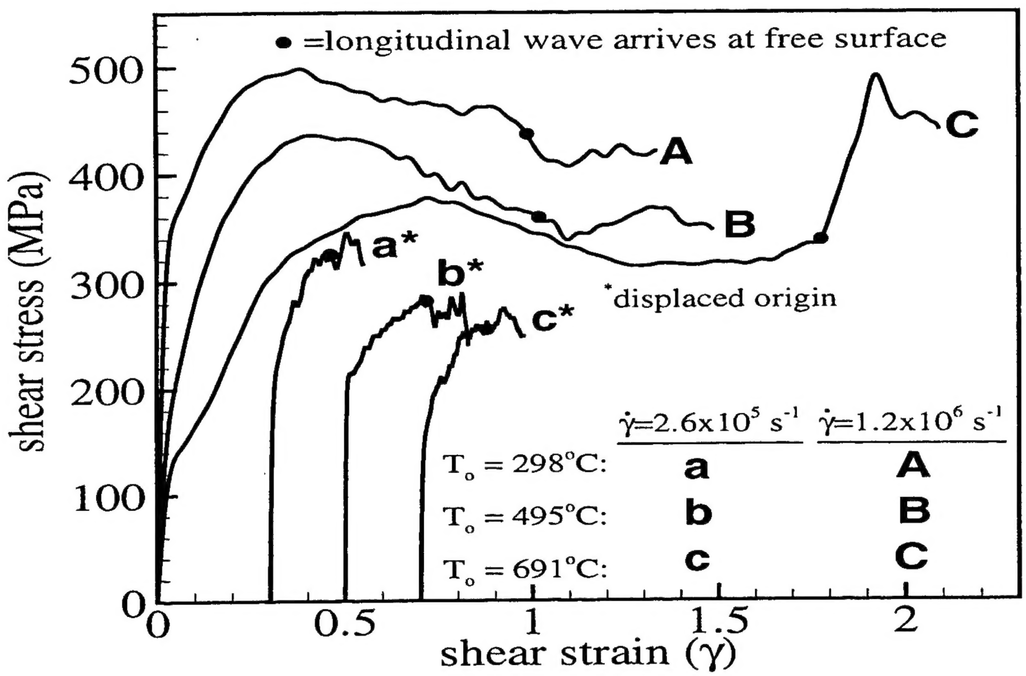

Figure 3: Strain-Rate and Temperature Dependence of Shearing Resistance of OFHC Copper

approximately 0.5; however, this softening is not unstable and eventually turns to flow at a constant stress or even resumed hardening. The records should be highly reliable up to the black circles at which time a reflected longitudinal wave arrives that, because of tilt, could cause a spurious change in the recorded transverse velocity (and therefore in the shear stress). Two particularly interesting features of this observed response of OFHC copper are the relatively strong rate sensitivity and the relatively weak thermal softening. The latter is especially striking in that a relatively large flow stress ($\approx 340MPa$ in shear) is maintained at absolute temperatures approaching 85% of the melting point.

Comparison of the measured response for the higher rate experiments with predictions of various popular constitutive models for OFHC copper (See Figure 4) shows that the flow stresses predicted by the various models are lower than those measured in the experiments. It appears that all of the models overestimate the thermal softening at very high strain rates and elevated temperatures. None of the models predict the softening and rehardening observed at larger strains.

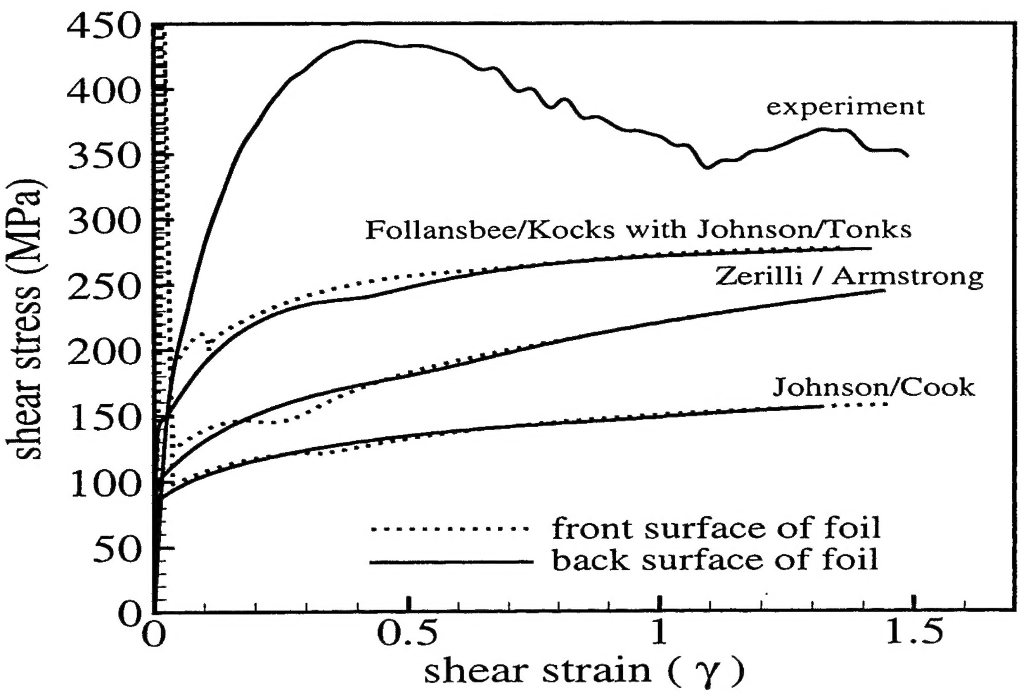

Figure 4: Comparison of Computed and Measured Responses for OFHC Copper ($\dot{\gamma} = 1.2 \times 10^6 s^{-1}$, $T_O = 495°C$)

2. Dynamic Plastic Response of Tantalum

The pressure-shear plate impact configuration has been used to measure the dynamic plastic response of tantalum at strain rates up to $5.0 \times 10^6 s^{-1}$. The objective of this investigation has been to extend the understanding of the shearing resistance of tantalum to strain rates above $10^5 s^{-1}$ as required for constitutive models that can be used for the regime of high strain rates and large strains that occur in explosively formed projectiles (EFPs). A second objective has been to determine whether or not there is a marked change in strain-rate sensitivity at very high strain rates, as has been observed previously for fcc metals. A summary of the results obtained so far for 25 μm thick foils is shown in Figure 5.

Shots KD9601, KD9605, KD9612 were at successively increasing strain rates from 0.42×10^6 to $0.84 \times 10^6 s^{-1}$; the remaining shots were at strain rates of approximately $1.5 \times 10^6 s^{-1}$. From the shots at higher strain rates it is evident that the stress-strain curves are of two types: monotonically increasing and increasing initially followed

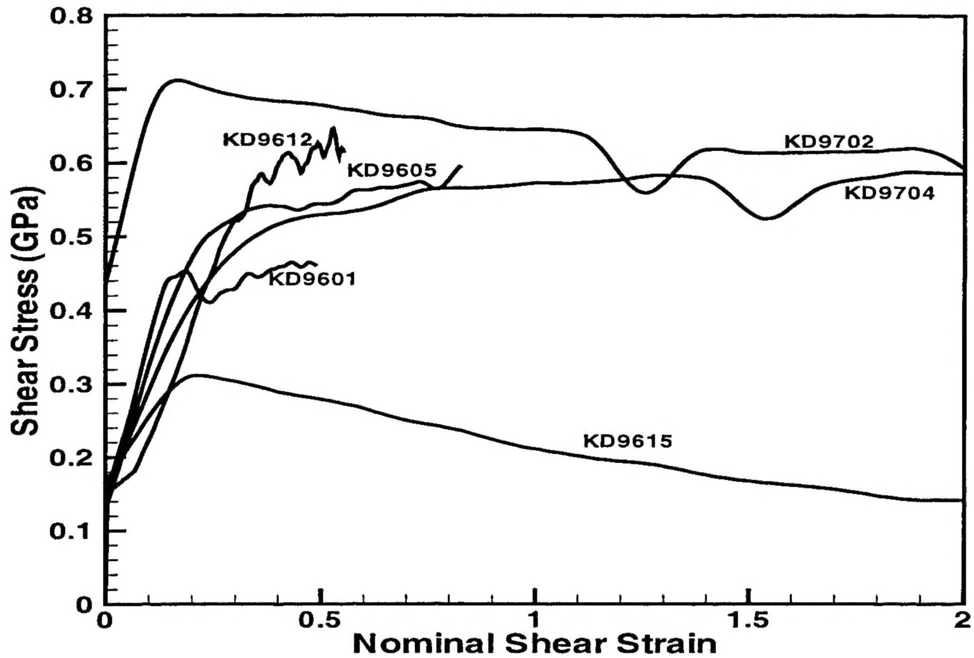

Figure 5: Dynamic Stress-Strain Curves for Tantalum at Shear Strain Rates of $10^6 s^{-1}$

by gradual decreasing. This difference in behavior appears to be related to rolling-induced texture as shots KD9702 and KD9704 are essentially identical except that the shearing is in the rolling direction for KD9702 and perpendicular to the rolling direction for KD9704; the specimen orientation for KD9615 is unknown. Similar contrasting behavior is observed for experiments on 0.10 μm foils; only monotonically increasing curves are obtained for 0.12 mm foils. During the remainder of the current investigation the role of texture at these very high strain rates will be sorted out through additional experiments on oriented specimens and TEM studies of final dislocation patterns and textures. From the work completed so far it has been established that the shearing resistance of tantalum at these very high strain rates is quite high, quite stable, and quite dependent on initial texture.

3. Dynamic Shear Failure of 4340 VAR Steel

A plate impact configuration developed originally to study dynamic tensile fracture (i.e. Mode I) at very high loading rates has been adapted to allow the investigation of dynamic shear fracture (i.e. Mode II and Mode III) and/or dynamic shear banding. The objective of this investigation is to understand the competition

between shear banding and fracture at the tip of a crack subjected to shear loading. Loading occurs by pressure-shear impact of a plate containing a midplane crack that extends halfway across the diameter. The relative dimensions of the flyer plate and the target plate are such that the shear wave arrives at the crack plane after the compressive pulse has passed through, leaving the crack plane unstressed. Rotation of the target plate about its normal allows the shear wave loading to be varied continuously from Mode II to Mode III. So far, attention has been restricted to Mode III because the wave analysis is less difficult. The experiments show that the crack is advanced by the impact loading and that the fracture surface consists of two distinct regions: an initial region consisting of large flat regions joined by narrow regions of ductile tearing, and a final region consisting of large voids separated by ligaments containing sheets of small voids. The final fracture region is similar to that observed in dynamic tensile fracture experiments on the same material and is believed to be due to tensile loading that results when the compressive pulse reflects from the rear surface and returns to the fracture plane. During the remainder of this investigation any uncertainty about the effect of a reflected tensile pulse will be removed by conducting additional experiments in which a transparent momentum trap will be introduced to prevent the return of a tensile pulse while allowing the continued recording of the transverse velocity of the rear surface of the sample.

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